

MICROBOLOMETER FOCAL PLANE ARRAY SYSTEMS AND METHODS

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CROSS-REFERENCE TO RELATED APPLICATIONS

This is a continuation-in-part application of U.S.
Application No. 10/085,226, filed February 27, 2002, which is
incorporated herein by reference in its entirety.

Technical Field

The present invention relates generally to focal plane
arrays and, more particularly, to microbolometer focal plane
arrays.

Background

Microbolometer structures are generally fabricated on
monolithic silicon substrates to form an array of
microbolometers, with each microbolometer functioning as a pixel
to produce a two-dimensional image. The change in resistance of
each microbolometer is translated into a time-multiplexed
electrical signal by circuitry known as the read out integrated
circuit (ROIC). The combination of the ROIC and the
microbolometer array are commonly known as a microbolometer
focal plane array (FPA). Additional details regarding
microbolometers may be found, for example, in U.S. Patent Nos.

5,756,999 and 6,028,309, which are herein incorporated by reference in their entirety.

Each microbolometer in the array is generally formed with two separate contacts, which are not shared with adjacent microbolometers in the array. One contact is used to provide a reference voltage for the microbolometer while the other contact provides a signal path from the microbolometer to the ROIC. A drawback of having two contacts per microbolometer is that the contacts do not scale proportionally as semiconductor processing technologies transition to smaller dimensions. Consequently, as microbolometer dimensions are reduced, the contacts consume a greater percentage of the area designated for the microbolometer, which reduces the area available for the desired resistive portion of the microbolometer and impacts microbolometer performance. As a result, there is a need for improved techniques for implementing microbolometer focal plane arrays.

SUMMARY

Systems and methods are disclosed herein to provide microbolometer focal plane arrays. For example, in accordance with an embodiment of the present invention, microbolometer focal plane array circuitry is disclosed for a microbolometer array having shared contacts between adjacent microbolometers. Each microbolometer may be selected by a method that may reduce the amount of crosstalk and capacitive degradations that may be associated with the shared contacts. Furthermore, the focal plane array circuitry may compensate for non-uniformities (e.g., a temperature coefficient of resistance) to allow operation over a wider temperature range than with conventional devices. Additionally, techniques are disclosed to calibrate the array

and/or circuitry, such as for example over a desired temperature range.

More specifically, in accordance with one embodiment of the present invention, a circuit includes a plurality of
5 microbolometers forming a microbolometer array, wherein contacts within the microbolometer array are shared among the microbolometers; means for selecting from among the microbolometers in the microbolometer array and providing a corresponding output signal; and means for providing temperature
10 compensation for the output signal.

In accordance with another embodiment of the present invention, a method of providing calibrated output signals from a microbolometer focal plane array having shared contacts includes selecting at least one row of the microbolometer focal
15 plane array to provide corresponding output signals from microbolometers in the row; providing a trim resistor value to provide temperature compensation for at least one microbolometer in the row; and providing an offset value to provide temperature compensation for at least one microbolometer in the row.

20 In accordance with another embodiment of the present invention, a microbolometer focal plane array includes a plurality of microbolometers forming a microbolometer array, wherein contacts within the microbolometer array are shared by the microbolometers; a first plurality of switches adapted to
25 provide a reference signal to respective ones of the plurality of microbolometers; and a second plurality of switches adapted to receive an output signal from respective ones of the plurality of microbolometers, wherein the first and second plurality of switches are initially asserted and deasserted,
30 respectively, with one of the switches from the first plurality deasserted prior to one of the switches from the second plurality being asserted which couple to the same contact, with

this switching pattern repeated for the first and second plurality of switches until the second plurality of switches are all asserted.

5 The scope of the invention is defined by the claims, which are incorporated into this section by reference. A more complete understanding of embodiments of the present invention will be afforded to those skilled in the art, as well as a realization of additional advantages thereof, by a consideration of the following detailed description of one or more
10 embodiments. Reference will be made to the appended sheets of drawings that will first be described briefly.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1a shows a circuit diagram illustrating a
15 microbolometer array and selection circuitry in accordance with an embodiment of the present invention.

Fig. 1b shows a circuit diagram illustrating a microbolometer array and selection circuitry in accordance with an embodiment of the present invention.

20 Fig. 1c shows a circuit diagram illustrating a microbolometer array and selection circuitry in accordance with an embodiment of the present invention.

Fig. 2a shows a timing diagram for the selection circuitry of Fig. 1a.

25 Fig. 2b shows a timing diagram for the selection circuitry of Fig. 1b.

Fig. 2c shows a timing diagram for the selection circuitry of Fig. 1c.

Fig. 3 shows a physical layout of a microbolometer array in accordance with an embodiment of the present invention.

Fig. 4 shows a physical layout of a microbolometer array in accordance with an embodiment of the present invention.

5 Fig. 5 shows a physical layout of a microbolometer array in accordance with an embodiment of the present invention.

Fig. 6 shows a physical layout of a microbolometer array in accordance with an embodiment of the present invention.

10 Fig. 7 shows a physical layout of a microbolometer array in accordance with an embodiment of the present invention.

Fig. 8 shows a block diagram illustrating a microbolometer focal plane array and associated circuitry in accordance with an embodiment of the present invention.

15 Fig. 9 shows a block diagram illustrating a microbolometer focal plane array and associated circuitry in accordance with an embodiment of the present invention.

Fig. 10a shows a circuit diagram illustrating a portion of a readout integrated circuit in accordance with an embodiment of the present invention.

20 Fig. 10b shows a circuit diagram illustrating a portion of a readout integrated circuit in accordance with an embodiment of the present invention.

25 Fig. 10c shows a circuit diagram illustrating a portion of a readout integrated circuit in accordance with an embodiment of the present invention.

Fig. 11 shows a circuit diagram illustrating a portion of a readout integrated circuit in accordance with an embodiment of the present invention.

Fig. 12 shows a flowchart of a calibration process in accordance with an embodiment of the present invention.

Fig. 13 shows a detailed flowchart for a step of the flowchart of Fig. 12.

5 Fig. 14 shows a detailed flowchart for a step of the flowchart of Fig. 12.

Fig. 15 shows a detailed flowchart for a step of the flowchart of Fig. 12.

10 Fig. 16 shows a detailed flowchart for a step of the flowchart of Fig. 12.

Fig. 17 shows a compensation process in accordance with an embodiment of the present invention.

Embodiments of the present invention and their advantages are best understood by referring to the detailed description
15 that follows. It should be appreciated that like reference numerals are used to identify like elements illustrated in one or more of the figures.

DETAILED DESCRIPTION

20 Fig. 1a shows a circuit 300 illustrating a microbolometer array and selection circuitry in accordance with an embodiment of the present invention. Circuit 300 includes microbolometers 302 and switches 304. Microbolometers 302 (which are separately
25 referenced as microbolometers 302(1) through 302(N), where N represents the desired number of microbolometers in a column) form at least a portion of an exemplary microbolometer array of at least one column of N rows, with adjacent (e.g., column neighbors within a column) microbolometers 302 sharing a contact

306. The number of columns and rows of the microbolometer array may vary, depending for example on the desired application, with circuit 300 replicated to form the desired number of additional columns. It should also be understood that reference to a
5 column or a row may include a partial column or a partial row and that the column and row terminology may be interchangeable, depending upon the application.

Switches 304 are employed to select the desired row within the microbolometer array. For example, Fig. 2a shows an
10 exemplary timing diagram 320 for the selection circuitry of Fig. 1a (circuit 300). Control signals (labeled SEL1 through SELN) are used to control corresponding switches 304 (e.g., transistors within the ROIC) to select the desired microbolometer row. For example, if the control signal SEL1 is
15 asserted, switches 304(1) are closed and microbolometer 302(1) receives a reference voltage (labeled VDETCOM and also referred to as Vbias, with its value set to, for example, ground or a desired voltage value) and provides a signal to associated or additional circuitry of the ROIC. In a similar fashion,
20 microbolometers 302(2) through 302(N) may be selected, for example, row by row in a sequential fashion as shown in Fig. 2a.

As shown in Fig. 1a, microbolometers 302 within circuit 300 share a contact (contact 306) with an adjacent microbolometer 302 within the column. By sharing contacts, the number of
25 contacts required for the microbolometer array is reduced and, consequently, the amount of area required for the contacts is reduced. However, this may affect the performance of the microbolometer array and hamper the ROIC's ability to capture data from the microbolometer array. For example, additional
30 parasitic capacitances, capacitive loading, and switch resistance may significantly degrade the array's performance. Furthermore, additional factors or non-uniformities may

contribute to the performance degradation, especially if temperature variations occur, such as for example temperature coefficient of resistance (TCR), heat capacity, thermal conductivity of each microbolometer 302, and self heating.

- 5 Techniques for minimizing one or more of these performance degradations are described in further detail herein.

Fig. 1b shows a circuit 330 illustrating a microbolometer array and selection circuitry in accordance with an embodiment of the present invention. Circuit 330 is similar to circuit 300
10 (Fig. 1a), but switches 304 are controlled in a different manner. For example, Fig. 2b shows an exemplary timing diagram 340 for the selection circuitry of Fig. 1b (circuit 340). Control signals (labeled EN1 through ENN and SEL1 through SELN) are used to control corresponding switches 304 to select the
15 desired microbolometer row.

For example, initially the control signals EN1 through ENN are asserted to close associated switches 304(1) through 304(N) and apply the reference voltage (VDETCOM) to microbolometers 302(1) through 302(N). The control signal SEL1 is asserted to
20 close associated switch 304(1), with microbolometer 302(1) providing a signal to associated or additional circuitry of the ROIC. The control signal EN1 is deasserted to open switch 304(1) and remove the reference voltage from microbolometer 302(1). The control signal SEL2 is then asserted to close
25 associated switch 304(2), with microbolometer 302(2) providing a signal to associated or additional circuitry of the ROIC.

In a similar fashion, microbolometers 302(3) through 302(N) may be selected, for example, row by row in a sequential fashion as shown in Fig. 2b. After sampling microbolometers 302(1)
30 through microbolometers 302(N), the control signals SEL1 through SELN are deasserted and timing diagram 340 may be repeated. By closing the select switches (e.g., switches 304) in this manner,

the detrimental parasitic resistance and capacitance characteristics may be minimized, thus providing improved performance. Therefore, by controlling switches 304 as illustrated in Fig. 2b, capacitive loading and parasitic capacitances may be reduced and the microbolometer array's performance improved.

Fig. 1c shows a circuit 350 illustrating a microbolometer array and selection circuitry in accordance with an embodiment of the present invention. Circuit 350 includes microbolometers 302 and switches 304. Microbolometers 302(1) through 302(6) form one column of microbolometers 302, while microbolometers 302(7) through 302(12) form another column of microbolometers 302 in the microbolometer array. It should be understood, however, that circuit 350 may include any number of microbolometers 302 to form the desired number of rows and that circuit 350 may be replicated to form the desired number of additional columns for the microbolometer array.

Microbolometers 302 within circuit 350 share contacts within a column, such as for example contacts 352 for a first column and contacts 354 for a second column. Microbolometers 302 within circuit 350 also share contacts between the first and second column, such as for example contacts 356, with microbolometers 302(2), 302(3), 302(8), and 302(9) sharing contact 356(1) and microbolometers 302(4), 302(5), 302(10), and 302(11) sharing contact 356(2).

Switches 304 are employed to select the desired row within the microbolometer array. For example, Fig. 2c shows an exemplary timing diagram 370 for the selection circuitry of Fig. 1c (circuit 350). Control signals (labeled SEL1,2; EN1; EN2,3; SEL3,4; EN4,5; and SEL5,6) are used to control corresponding switches 304 to select the desired microbolometer row.

For example, the control signal SEL1,2 is asserted to close associated switches 304(5) and 304(10) and the control signal EN1 is asserted to close associated switch 304(4) and apply the reference voltage (VDETCOM) so that microbolometers 302(6) and 302(12) can provide their signals to associated or additional circuitry of the ROIC. The control signal EN1 is then deasserted to open switch 304(4), the control signal EN2,3 is then asserted to close associated switch 304(3) and apply the reference voltage (VDETCOM) so that microbolometers 302(5) and 302(11) can provide their signals to associated or additional circuitry of the ROIC.

The control signal SEL1,2 is then deasserted to open switches 304(5) and 304(10) followed by the control signal SEL3,4 asserted to close associated switches 304(6) and 304(9) so that microbolometers 302(4) and 302(10) can provide their signals to associated or additional circuitry of the ROIC. Thus, this process may continue in a similar fashion to read out the signals from microbolometers 302(1) through 302(3) and 302(7) through 302(9), for example, row by row in a sequential fashion as shown in Fig. 2c for the associated control signals of circuit 350.

Fig. 3 shows a physical layout of a microbolometer array 500 in accordance with an embodiment of the present invention. Microbolometer array 500 includes microbolometers 502 and 504, which are arranged as one column of two rows and may represent two of microbolometers 302 (e.g., microbolometers 302(1) and 302(2) in Figs. 1a or 1b) within circuit 300 or 330.

Microbolometers 502 and 504 each include a resistive material 506, which is formed of a high temperature coefficient of resistivity (TCR) material (e.g., vanadium oxide (VO_x) or amorphous silicon). Resistive material 506 is suspended on a bridge 508, with resistive material 506 coupled to its contacts

514 via legs 512. Legs 512 attach to resistive material 506 through a resistive material contact 510 (e.g., a leg metal to resistive metal contact and labeled VO_x contact). In general, microbolometers 502 and 504 are constructed in a conventional manner with conventional materials, but share contact 514(3).

Fig. 4 shows a physical layout of a microbolometer array 540 in accordance with an embodiment of the present invention. Microbolometer array 540 is similar to microbolometer array 500 (Fig. 3), but contacts 514 are oriented in a different manner, as shown, relative to microbolometers 502 and 504. Microbolometer array 540 may allow a stronger bond between leg 512 and contact 514 and/or may be easier to form during the manufacturing process.

Microbolometer array 500 (Fig. 3) or microbolometer array 540 (Fig. 4) may be implemented as an array of any desired size (e.g., 644 by 512 pixels with each pixel (or microbolometer) 25 by 25 μ m in size). For example, Fig. 5 shows a physical layout of a microbolometer array 550 in accordance with an embodiment of the present invention. Microbolometer array 550 is a four-by-four array having microbolometers implemented as described in reference to Fig. 3.

Fig. 6 shows a physical layout of a microbolometer array 600 in accordance with an embodiment of the present invention. Microbolometer array 600 includes microbolometers 602, 604, 606, and 608, which are arranged as two columns of two rows (e.g., microbolometers 602 and 604 forming one column and microbolometers 606 and 608 forming the other column).

In general, microbolometers 602 through 608 are constructed in a manner similar to, for example, microbolometer 502 (Fig. 3). However, microbolometers 602 through 608 are arranged to all share contact 514(3), shown centrally within Fig. 6.

Thus, microbolometers 602 through 608 may represent, for example, four of microbolometers 302 (e.g., microbolometers 302(4), 302(5), 302(10), and 302(11) in Fig. 1c) of circuit 350. Furthermore, microbolometer array 600 may be replicated to
5 implement an array of any desired size. For example, Fig. 7 shows a physical layout of a microbolometer array 650 in accordance with an embodiment of the present invention. Microbolometer array 650 is a four-by-four array having microbolometers implemented as described in reference to Fig. 6.

10 Fig. 8 shows a block diagram 800 illustrating a microbolometer focal plane array 802, with uniformity-correction circuitry, and interface system electronics 818 in accordance with an embodiment of the present invention. Microbolometer focal plane array 802 includes a microbolometer array (labeled
15 unit cell array) and a readout integrated circuit (ROIC) having control circuitry, timing circuitry, bias circuitry, row and column addressing circuitry, column amplifiers, and associated electronics to provide output signals that are digitized by an analog-to-digital (A/D) converter 804.

20 The microbolometer array (unit cell array) of microbolometer focal plane array 802 may be formed by microbolometers having shared contacts and selection switches as described in reference to Figs. 1-7. The ROIC of microbolometer focal plane array 802 may be employed to control the selection
25 switches (i.e., switches 304 of Fig. 1a, 1b, or 1c which may be formed as part of the ROIC) to select the desired microbolometers for obtaining the desired output signals. The column amplifiers and other circuitry of the ROIC may otherwise be constructed in a conventional manner.

30 The A/D converter 804 may be located on or off the ROIC. The output signals from A/D converter 804 are stored in a frame memory 806. The data in frame memory 806 is then available to

image display electronics 808 and a data processor 812, which also has a data processor memory 810. A timing generator 814 provides system timing.

5 Data processor 812 generates uniformity-correction data words, which are loaded into a data register load circuitry 816 that provides the interface to load the correction data into the ROIC. In this fashion the digital-to-analog converters, and other variable circuitry, which control voltage levels, biasing, circuit element values, etc., are controlled by data processor
10 812 to provide the desired output signals from microbolometer focal plane array 802.

Fig. 9 shows a block diagram 280 illustrating a microbolometer focal plane array 282, with uniformity-correction circuitry, and interface system electronics 283 in accordance
15 with an embodiment of the present invention. Block diagram 280 is similar to block diagram 800, but includes additional techniques for providing, for example, temperature compensation and/or correction for various non-uniformities, as described in further detail herein (e.g., in reference to Figs. 10-17).

20 Microbolometer focal plane array 282 includes a microbolometer focal plane array (labeled unit cell array) and a readout integrated circuit (ROIC) having control circuitry, timing circuitry, bias circuitry, row and column addressing circuitry, column amplifiers, and associated electronics to
25 provide output signals that are digitized by an analog-to-digital (A/D) converter 284.

The microbolometer array (unit cell array) of microbolometer focal plane array 282 may be formed by microbolometers having shared contacts and selection switches as
30 described in reference to Figs. 1-7. The ROIC of microbolometer focal plane array 282 may be employed to control the selection

switches (i.e., switches 304 of Fig. 1a, 1b, or 1c which may be formed as part of the ROIC) to select the desired microbolometers for obtaining the desired output signals.

The A/D converter 284 may be located on or off the ROIC.

5 The output signals from A/D converter 284 are adjusted by a non-uniformity correction circuit (NUC) 285, which applies temperature dependent compensation (e.g., Lagrange Offset, Temperature Dependent Gain, and additional Offset) as discussed herein, such as for example in reference to Figs. 12-17. After
10 processing by NUC 285, the output signals are stored in a frame memory 286. The data in frame memory 286 is then available to image display electronics 288 and a data processor 292, which also has a data processor memory 290. A timing generator 294 provides system timing.

15 Data processor 292 generates uniformity-correction data words, which are loaded into a correction coefficient memory 298. A data register load circuitry 296 provides the interface to load the correction data into readout integrated circuit 282. In this fashion the variable resistors, digital-to-analog
20 converters, and other variable circuitry, which control voltage levels, biasing, circuit element values, etc., may be controlled by data processor 292 so that the output signals from the readout integrated circuit are uniform over a wide temperature range.

25 Fig. 10a shows a circuit 1000 illustrating a portion of a readout integrated circuit 1002 and circuit 330 (e.g., a portion of a microbolometer array, such as a row or a column) in accordance with an embodiment of the present invention. Circuit 1002 provides temperature compensation for circuit 330 in
30 accordance with an embodiment of the present invention. It should be understood that circuit 330 is shown in an exemplary fashion and that circuit 300 (Fig. 1a) or circuit 350 (Fig. 1c)

may be substituted for circuit 330 (e.g., in Figs. 10a, 10b, or 11).

Circuit 1002 includes supply voltage 40 (and may provide the reference voltage labeled VDETCOM), thermally-shortened microbolometer 36, resistors 26 and 38, transistor 30, amplifier 32, and a digital-to-analog converter (DAC) 34. As explained in detail herein, circuit 1002 provides substrate temperature compensation and temperature coefficient of resistance (TCR) mismatch compensation for the active and load microbolometers.

The active microbolometer is the thermally isolated microbolometer, selected from circuit 330 as explained above, which receives incident infrared radiation. The active microbolometer is biased by the reference voltage (VDETCOM) and a load current (I_{bias}). Amplifier 32 provides the gate bias for transistor 30 (an NMOS transistor), while DAC 34 is used to set an amplifier reference voltage and control amplifier 32 to set the appropriate gate bias for transistor 30. Alternatively, amplifier 32 can be eliminated and DAC 34 used to set the appropriate gate bias directly for transistor 30. A load circuit or bias circuit includes supply voltage 40, resistor 38, microbolometer 36 (thermally shorted (to the substrate) load microbolometer), transistor 30, and amplifier 32 with DAC 34, which are used to establish the load current (I_{bias}).

Microbolometer 36 is used as a substrate temperature compensated load. Supply voltage 40 is set to optimize the operating point for circuit 1002 by setting the nominal voltage drop across microbolometer 36. An output voltage (V_{out}) 42 of circuit 1002 is provided at a node 41.

An amplifier (such as an amplifier 28 as illustrated in Fig. 11) may amplify a voltage at node 41 to provide an output voltage (V_{out}) 42. The amplifier is an exemplary circuit

element to provide amplification or buffering for the voltage at node 41, if desired. As with amplifier 32, a DAC may provide a reference voltage (V_{ref}) for the amplifier or the reference voltage may be at a set voltage level (e.g., ground). It should
5 be apparent that output voltage (V_{out}) 42 may be translated, amplified, or converted by amplification or integration processes and/or other well known signal processing techniques.

For example, a transimpedance amplifier 258 (as illustrated in circuit 1050 of Fig. 10b) may be employed within a portion of
10 a readout integrated circuit 1052 to provide the output voltage 42. In addition, a DAC 256 may control the gate terminal of transistor 30, while a DAC 254 controls a gate terminal of a transistor 252 coupled to resistor 26. Thus, transistor 252 along with transistor 30 may control the bias applied to the
15 active microbolometer (selected from circuit 330) and microbolometer 36, respectively. Specifically, DAC 254 adjusts the offset by controlling the bias applied to the active microbolometer in combination with resistor 26 via transistor 252. Likewise, DAC 256 adjusts the offset by controlling the
20 bias applied to microbolometer 36 in series with resistor 38 via transistor 30.

Transimpedance amplifier 258, having an impedance element 260 (e.g., a capacitor, a switched capacitor network, or a thermally-shorted microbolometer that may compensate gain as a
25 function of substrate temperature), translates the current level flowing into transimpedance amplifier 258 into a voltage level at output voltage (V_{out}) 42. Consequently, DACs 254 and 256 determine the amount of current flowing through respective microbolometers (i.e., the active microbolometer and
30 microbolometer 36) and also into transimpedance amplifier 258 and, thus, set the offset and reference level of output voltage (V_{out}) 42. DACs 254 and 256 can be calibrated, as discussed

herein, for a single temperature or over a desired operating temperature range for each microbolometer in the FPA array.

In terms of general circuit operation for circuit 1000 (Fig. 10a), as incident infrared radiation levels increase, the temperature of the active microbolometer (i.e., one of microbolometers 302(1) through 302(N)) increases, which lowers its resistance and reduces the voltage drop across it and thus, increases the voltage level at the drain terminal of transistor 30 (i.e., node 41). In general, the change in the voltage drop across the active microbolometer causes a change in output voltage (Vout) 42. Therefore, as incident infrared radiation levels increase or decrease, this is reflected by the voltage level of output voltage (Vout) 42 increasing or decreasing, respectively.

In general, supply voltage 40 is used to adjust the load current and thereby optimize the operating point of the circuit by setting output voltage 42 at a desired point within a range of output circuitry voltage levels. Specifically, by setting the appropriate gate bias of transistor 30 and appropriate voltage level of supply voltage 40, the output voltage (Vout) 42 is adjusted.

For example, supply voltage 40 may be a single voltage level set for the entire array of microbolometers. Amplifier 32 and DAC 34 are then used to supply a unique voltage bias to each corresponding thermally-shorted microbolometer 36 in the FPA to provide a fine adjustment or offset to the load voltage or the load current (Ibias). This corrects for the individual offset errors in the output signals from each of the thermally-isolated microbolometers (e.g., the active microbolometers). By adjusting the offset for each microbolometer circuit, the nominal output voltage level of output voltage (Vout) 42 for each circuit is adjusted to fall within a desired range.

To address the relative mismatch in temperature coefficient of resistance (TCR) between the active microbolometer (in circuit 330) and microbolometer 36 (the load microbolometer), resistors 26 and 38 are provided. Resistor 26 is a variable resistor to generally provide fine adjustments to the composite TCR value of the active microbolometer portion of the circuit relative to the load microbolometer portion of the circuit. Thus, for the voltage divider network of resistors, resistor 26 adjusts the composite TCR of the active microbolometer and resistor 26 relative to microbolometer 36 and resistor 38. As an example, circuit values for these circuit elements are 100 K Ω and 300 K Ω for the active microbolometer and microbolometer 36, respectively, but these values are not limiting and may vary over a large range, such as for example 50-200 K Ω and 150-600 K Ω , respectively. Exemplary circuit values for resistors 26 and 38 may, for example, vary within 0-10 K Ω and 0-30 K Ω , respectively, but this range is not limiting and may vary over a wider range of values.

Resistors 26 and resistors 38 are typically resistors having a different TCR (generally lower) than their corresponding microbolometers (i.e., the active microbolometer and microbolometer 36). For example, resistor 26 may have a low TCR and the active microbolometer may have a higher TCR relative to microbolometer 36. Consequently, by the proper selection of resistance value for resistor 26, the combination of resistor 26 and the active microbolometer provides a TCR that is much closer to the TCR of microbolometer 36 (or the TCR of the combination of microbolometer 36 and resistor 38 if resistor 38 is present) than is the TCR of solely the active microbolometer. Therefore, the performance and behavior of each microbolometer within the array is vastly improved over a range of substrate temperatures.

The following equation illustrates the combined or composite TCR for a microbolometer in series with a variable resistor (i.e., the active microbolometer and resistor 26) as a function of temperature.

$$5 \quad TCR = (TCR_{Bo} R_B(T) / (R_B(T) + R_{Trim}))$$

TCR, TCR_{Bo} , $R_B(T)$, and R_{Trim} represent the effective combined TCR (labeled TCR), the TCR of the microbolometer (labeled TCR_{Bo}), the resistance of the microbolometer at a given temperature (labeled $R_B(T)$), and the resistance value of the variable resistor (e.g.,
 10 to a first order constant as a function of temperature and labeled R_{Trim}), respectively. This equation illustrates how the combined TCR is adjusted depending upon the resistance value of the variable resistor.

Resistor 38 provides the coarse adjustment for circuit
 15 1000. Consequently by setting resistor 26, temperature compensation is provided for the mismatch in relative TCR between the active microbolometer and the load microbolometer. A calibration procedure as a function of the substrate temperature is performed to determine the appropriate value for
 20 resistors 26 and 38. Details of an exemplary calibration procedure are provided herein.

The relative mismatch in TCR is driven by various factors, such as pulse bias heating, non-uniformities among microbolometers, and relative contact resistance between the
 25 active microbolometer and the load microbolometer and the substrate. Ideally, by accounting for the relative mismatch in TCR and offset as a function of substrate temperature, the output voltage for a given microbolometer circuit will be well behaved. For example, for a certain level of received incident
 30 infrared radiation, the microbolometer circuit output voltage may fall within a small percentage (e.g., twenty percent) of the

minimum and maximum dynamic range over the desired substrate temperature range (e.g., from 250 to 350°C).

It should be understood that Fig. 10a is an exemplary circuit to illustrate the relative TCR mismatch and temperature compensation techniques and that numerous modifications and variations are possible in accordance with the principles of the present invention. For example, resistor 38 may not be necessary, depending upon the characteristics of the microbolometers within the array. Resistors 26 and 38 may be implemented as parallel resistance, rather than series, relative to respective microbolometers, or some combination of series and parallel resistance may be implemented. The circuit arrangement may also vary, such as by interchanging the positions of resistor 26 and resistor 38 or the positions of circuit 330 and microbolometer 36. Furthermore, circuit polarities may be inverted, such as for example by inverting power supplies and substituting p-channel for n-channel transistors or vice versa as would be known by one skilled in the art. Additionally, one or more techniques discussed or referenced herein may be combined or selectively implemented, depending upon the application or various other factors.

As an example of an alternative implementation, in accordance with an embodiment of the present invention, Fig. 10c shows a circuit 1070 illustrating a portion of a readout integrated circuit in accordance with an embodiment of the present invention. Circuit 1070 is similar to circuit 1050 of Fig. 10b, but resistor 26 is removed and a current source 272 is provided. The amount of current flowing through the active microbolometer (i.e., one of microbolometers 302(1) through 302(N)) to produce a microbolometer bias current (labeled I_{biasB}) is reduced by the contribution of current by current source 272. Therefore, the voltage across the active

microbolometer is reduced and the change in the contribution of current through the active microbolometer to the microbolometer bias current (I_{biasB}) as a function of temperature is fractionally reduced. Thus, current source 272 has effectively
5 lowered the temperature coefficient of resistance (TCR) of the active microbolometer.

Current source 272 may be employed to provide temperature compensation within the readout integrated circuit. Current source 272, for example, may be a fixed or a variable current
10 source and may be varied or set in a similar fashion as discussed herein for resistor 26 (e.g., as discussed in reference to Figs. 12-17) to provide temperature compensation.

In general as an example, circuit 1000 in Fig. 10a (as well as, for example, other circuits illustrated herein) can be
15 implemented in an array configuration, with a portion of circuit 1000 placed in the unit cell while the remainder is placed outside of the unit cell, such as in the column amplifier. For example, circuit 330 may be solely placed within the unit cell array (along with associated selection circuitry, if desired,
20 such as switches 304).

Fig. 11 shows a circuit 1100 illustrating a portion of a readout integrated circuit 1102 and circuit 330 (or a portion of a microbolometer array) in accordance with an embodiment of the present invention. Circuit 1102 provides temperature
25 compensation for circuit 330 in accordance with an embodiment of the present invention.

Circuit 1100 is similar to circuit 1000 of Fig. 10a, but includes a reference path 62. Reference path 62 includes thermally shorted microbolometers 66 and 74, variable resistor
30 68, a transistor 70, an amplifier 72, and a DAC 64.

DAC 64 provides a reference voltage to amplifier 72, which is used to appropriately bias transistor 70. DAC 64 and resistor 68 are adjusted to provide a reference voltage for amplifier 28. Amplifiers 32 and 72 may have their reference
5 voltage provided by a DAC or the reference voltage may be provided to amplifier 32 and/or 72 by a set reference voltage level (e.g., ground). Furthermore, microbolometer 66 and/or microbolometer 74 may be replaced by a resistor, which would provide the necessary temperature dependent reference behavior.

10 Reference path 62 will be affected by changes in substrate temperature in a similar fashion as the remaining portions of circuit 1102. Consequently, the reference voltage to amplifier 28 will vary in temperature and, therefore, reference path 62 provides additional temperature compensation. Additionally,
15 power supply noise from supply voltage 40 and the reference voltage (VDETCOM) are reduced by the common mode input to amplifier 28.

Fig. 12 shows a top-level flowchart 100 of a calibration process in accordance with an embodiment of the present
20 invention. Flowchart 100 includes steps 102 through 110 for calibrating a microbolometer FPA. Step 104 is a required step and steps 102 and 106 through 110 may be optional steps, depending upon the microbolometer FPA behavior or performance, the desired application, and required performance. Figs. 13
25 through 16 provide exemplary detailed flowcharts pertaining to steps 102 through 110.

The external resistance is calibrated in step 102. The term "external resistance" refers, for example, to the resistance of a resistor such as resistor 38 of Fig. 10a, which
30 is typically placed outside of the unit cell and is not part of the variable (or trim) resistance (e.g., resistor 26 of Fig. 10a). The external resistance or the value of the external

resistor may be digitally selectable and/or may be a global resistor and may be on or off-chip (i.e., on or off the FPA or the ROIC). Therefore, one external variable resistor or a few external variable resistors may be sufficient for a large
5 microbolometer FPA. For example, as each microbolometer in the array is sampled, the global external resistor is set to its calibrated value, determined during the calibration process, corresponding to that particular microbolometer, column, group, or array of microbolometers. As discussed above, depending upon
10 the behavior of the microbolometers in the FPA, an external resistor may not be required.

The variable resistance and offset is calibrated for each microbolometer in step 104. The variable resistance or trim resistance refers, for example, to the resistance of a resistor
15 (a trim resistor) such as resistor 26 in Fig. 10a. For example, step 104 determines the amount of resistance to be placed in series with each active microbolometer in the FPA. Step 104 also determines the amount of offset to be applied for each microbolometer in the FPA. As an example, the determined offset
20 for each microbolometer may be set by using DAC 34 to control the gate bias of transistor 30 via amplifier 32 in Fig. 10a.

Step 106 provides fine offset correction calibration for each microbolometer circuit output over the desired substrate temperature range. Various techniques may be employed to
25 provide a fine correction to each microbolometer circuit output after step 104 and possibly step 102 are performed, because these steps then provide a correctable microbolometer circuit output over a wide range of substrate temperature. The techniques may include various mathematical best-fit or offset
30 correction algorithms or look-up table methods to determine the fine offset correction factor for a given temperature. For example, Lagrange terms enable a polynomial offset correction to

be generated in real-time for each microbolometer that compensates for variations in microbolometer circuit output over FPA substrate temperature.

- Step 108 provides gain calibration for each microbolometer.
- 5 The gain terms normalize the response of each microbolometer to incident infrared radiation. This step may simply determine the gain term independent of FPA substrate temperature or, in a more general fashion, determine the gain term as a function of FPA substrate temperature. Similar mathematical best-fit,
- 10 correction algorithms, or look-up table methods can be provided for these terms. Step 110 provides an additional fine offset, if required, for each microbolometer. The offset also may be a function of FPA substrate temperature.

- Fig. 13 is a detailed flowchart 120 for step 102 of
- 15 flowchart 100 in Fig. 12. Flowchart 120 provides exemplary calibrations steps for calibrating the external resistor. Step 122 sets the trim resistor for each microbolometer to a target value, such as the median value of the trim resistor range. The FPA temperature is then set to a value (i.e., T1) within the
- 20 desired calibration or operation temperature range (step 124). For example, T1 may represent the value of the minimum operating temperature range. The external resistor is then set to one of its "n" possible values (step 126) and the offset is calibrated for each microbolometer (step 128), where the offset may be
- 25 calibrated using the procedure described below. The offset value and microbolometer circuit output value, obtained after application of the offset value, is stored (step 130) and steps 126 through step 128 are repeated for each of the n possible external resistor values (step 132). The result is n pairs of
- 30 external resistor and offset values along with each corresponding microbolometer circuit output value.

The FPA temperature is then changed to another value (e.g., T2) within the desired calibration range (step 134). The stored external resistor and offset values are applied, for each value of n, and the microbolometer circuit output value is recorded (step 136). For each value of n, step 138 calculates the difference between the microbolometer circuit output from step 136 (i.e., at T1) and the microbolometer circuit output from step 132 (i.e., at T2) and then calculates the average difference across the full array of microbolometers. Step 140 selects the external resistor value corresponding to the smallest average difference obtained from step 138, with this resistor value being the calibrated value of the external resistor for the entire microbolometer FPA.

Fig. 14 is a detailed flowchart 150 for the trim resistance calibration in step 104 of flowchart 100 in Fig. 12. Flowchart 150 provides exemplary calibration steps for calibrating the trim resistor. Step 152 sets the FPA substrate temperature to one extreme of the desired operating or calibration temperature range (e.g., T1). The trim resistor is set to one of "m" possible values (step 154), such as the minimum value, and then the offset is calibrated (step 156) using a procedure, such as the one described below. The offset value and the resulting microbolometer circuit output value, after application of the offset value, are recorded for the given trim resistor value (step 158). Step 160 repeats steps 154 through 158 for each of the m possible trim resistor values, which results in m pairs of trim resistor/offset values and corresponding microbolometer circuit output values.

The FPA substrate temperature is then changed to a value (T2) at the opposite extreme as the prior value (T1) of the desired calibration or operating temperature range (step 162). For each value of m, the corresponding trim resistor value and

offset value obtained in steps 154 through 160 are applied and the microbolometer circuit output value is recorded (step 164). For each value of m (Fig. 14 - step 166), the difference is calculated between the microbolometer circuit output from step 5 164 (i.e., at temperature T_2) and the microbolometer circuit output obtained from step 158 (i.e., at temperature T_1). Step 168 selects the trim resistor value and associated offset value that corresponds to the minimum difference from the results of step 166. These values are the calibrated values for the trim 10 resistor and offset. Note that, if desired, the offset can be re-calibrated at a different FPA temperature value or with a different target value. This would provide a wider temperature operating range and more well-behaved performance.

For step 104 of flowchart 100 in Fig. 12, the offset value 15 is determined for each microbolometer in the FPA. The offset value, for example, can be determined for each microbolometer by using a binary search to find the offset value that adjusts the microbolometer circuit output value closest to a desired value (i.e., microbolometer circuit output target value). The 20 temperature of the FPA substrate and other parameters, such as the flux incident on the FPA, should generally not vary substantially while the offset calibration is in process.

Fig. 15 is a detailed flowchart 180 for step 106 of flowchart 100 in Fig. 12. Flowchart 180 provides exemplary 25 calibrations steps for calibrating the fine offset correction (e.g., Lagrange) terms for a microbolometer in the FPA array. However, the exemplary procedure could be employed in the more general case to calibrate many pixels simultaneously. Step 182 sets the FPA temperature to a value within the desired 30 calibration or operating range and records the measured temperature value (having temperature units, such as Kelvin or Celsius, or units of volts that correspond to a given

temperature). For this temperature, the microbolometer circuit output is recorded after the application of the calibrated trim resistor and offset values (step 184).

5 The FPA temperature is then changed, at step 186, to another value within the desired temperature range and steps 182 and 184 are repeated. Step 188 repeats step 186 a minimum of $K+1$ times, where K represents the desired order of the polynomial correction. For example, a minimum of four terms is stored if the third order polynomial correction is desired. The
10 polynomial correction results generally improve if two of the $K+1$ points are at the opposite extremes of the desired calibration range.

The gain of each microbolometer can be calibrated using a two-point calibration process (e.g., at two different values of
15 incident flux) at any arbitrary FPA temperature. Alternatively, the gain of each microbolometer can be calibrated as a function of FPA temperature, such as in the calibration process described below. Both procedures are similar to the fine offset (e.g., Lagrange) correction described above in reference to Fig. 15,
20 but the two procedures (i.e., gain and fine offset) differ from each other in that instead of storing each microbolometer circuit output at a single value of incident flux, each microbolometer circuit output is stored for two values of incident flux.

25 Fig. 16 is a detailed flowchart 200 for step 108 of flowchart 100 in Fig. 12. Flowchart 200 provides exemplary calibration steps for calibrating the gain of each microbolometer. Step 202 sets the FPA temperature to a value within the desired calibration or operating range and the
30 temperature value is recorded (in units of temperature, such as Kelvin or Celsius, or in units of voltage that correspond to a given temperature). Step 204 records the microbolometer circuit

output difference for two flux levels or responsivity for that temperature for each microbolometer. Step 206 changes the FPA temperature to another value within the calibration or operating range and the temperature value and each microbolometer circuit output is recorded. Step 206 is repeated (in step 208) a minimum of $K+1$ times, where k represents the desired order of the polynomial fit of the gain terms.

Fig. 17 illustrates a compensation process 220 in accordance with an embodiment of the present invention.

10 Compensation process 220 illustrates generally the overall compensation process for providing an optimal output from each microbolometer in the FPA over the desired FPA temperature range. The microbolometer FPA is represented symbolically by an FPA 222. As shown, each microbolometer in the array receives a trim resistor (R_{trim_i} , where i ranges from $1 \leq i \leq$ maximum number of microbolometers in the array) and an offset calibration ($Offset_i$) adjustment. The trim resistor calibration and the offset calibration adjust each microbolometer circuit output over the calibrated temperature range. An external resistor (R_{ext}) calibration is also optionally performed as described above, depending upon microbolometer FPA behavior. There may be an external resistor digitally selectable for each microbolometer or there may be one or more global external resistors that are calibrated for the entire microbolometer FPA or some corresponding portion of the microbolometer FPA.

The microbolometer circuit outputs from FPA 222 are combined in block 224 with the calibrated temperature-dependent fine (e.g., Lagrange) offset 230. The fine offset may be determined in any of a number of methods or techniques, as discussed herein. Fig. 17 refers to the fine offset as Lagrange offset 230, which is one exemplary method, but the fine offset is not intended to be limited solely to this exemplary method.

Lagrange offset 230 provides the calibrated polynomial correction values for each microbolometer circuit output, which can be summed with each microbolometer circuit output from FPA 222.

5 The application of Lagrange offset 230 refines the microbolometer circuit output behavior and provides more uniform data at the data processor (i.e., reduces the curve or bow in microbolometer circuit output over temperature). Lagrange offset 230 receives as inputs the measured substrate temperature
10 and the Lagrange terms (Lagrange Term_i), which are used to generate the Lagrange offset terms uniquely for each microbolometer in the array.

A block 226 receives the microbolometer circuit outputs, after application of the Lagrange offsets, and multiplies the
15 microbolometer circuit outputs by a corresponding calibrated temperature dependent gain 232. The gain adjusts each microbolometer circuit output to provide a more uniform response to incident flux. As shown, the gain is temperature dependent and receives as inputs the measured substrate temperature and
20 the gain terms (Gain Term_i), which are used to generate the temperature dependent gain uniquely for each microbolometer in the array.

A block 228 receives the microbolometer circuit outputs, after application of the gain adjustment, and sums the
25 microbolometer circuit outputs with additional offset terms (Offset_i), with the offset for block 228 typically differing from the offset input to FPA 222. For example, the offset term is updated periodically during camera operation using a shutter, a chopper, or a scene-based algorithm.

30 It should be appreciated that the implementation of the trim resistor (or current source 272) within each microbolometer

circuit provides the correctable microbolometer FPA performance over a wide temperature range. The correctable microbolometer FPA performance over the calibrated temperature range then permits the application of Lagrange offset, gain, and offset
5 calibration over the wide calibrated temperature range. It should also be appreciated that the principles of this invention may be implemented or applied to a wide variety of circuit devices and materials. Accordingly, the embodiments described herein are only exemplary of the principles of the invention and
10 are not intended to limit the invention to the specific embodiments disclosed.

Embodiments described above illustrate but do not limit the invention. It should also be understood that numerous modifications and variations are possible in accordance with the
15 principles of the present invention. Accordingly, the scope of the invention is defined only by the following claims.